Toward a Global 1/25° HYCOM Ocean Prediction System with Tides

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LONG-TERM GOALS

The overall technical goal is to implement a 1/25° horizontal resolution global ocean prediction system based on the HYbrid Coordinate Ocean Model (HYCOM) with tides and dynamic sea ice. The scientific goals include but are not limited to a) evaluation of the internal tides representation in support of field programs, b) data assimilation in the presence of tides, c) evaluation of the model's ability to provide useful boundary conditions to high resolution coastal models, d) interaction of the open ocean with ice, e) shelf–deep ocean interactions, f) upper ocean physics including mixed layer/sonic depth representation, g) mixing, etc.

OBJECTIVES

Perform the R&D necessary to develop, evaluate, and investigate the dynamics of 1/25° global HYCOM with tides coupled to CICE (the Los Alamos sea ice model) with atmospheric forcing only, with data assimilation via NCODA (NRL Coupled Ocean Data Assimilation), and in forecast mode. Work closely with NRL Stennis to incorporate advances in dynamics and physics from the science community into the HYCOM code maintained by the Navy.

APPROACH

A series of HYCOM configurations is used to (a) evaluate internal tides representation, (b) implement a configuration for data assimilation in the presence of tides, (c) investigate the interaction of the open ocean with ice, and (d) investigate the impact of horizontal resolution on Gulf Stream dynamics (not reported due to space limit). HYCOM development is the result of collaborative efforts among the Florida State University, University of Miami, and the Naval Research Laboratory (NRL) as part of the multi-institutional HYCOM Consortium for Data-Assimilative Ocean Modeling (Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004). This effort was funded by the National Ocean Partnership Program (NOPP) to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (Chassignet et al., 2009). HYCOM has been configured globally and on basin scales at up to 1/25º (~3.5 km mid-latitude) resolution. More details on the latest global simulations can be found at http://www.hycom.org and in the separate ONR reports by A. Wallcraft (NRL) and B. Arbic (UM).

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RESULTS

Tides

The tidal dynamic in the Gulf of Mexico has an extensive literature and all studies have always considered only bottom friction to be the main tidal dissipation mechanism in the domain. The goals of this study are twofold: 1) validate the tides (external and internal) in the Gulf of Mexico using HYCOM (without data assimilation), and 2) investigate the importance of the tidal conversion process in the domain as a function of the model resolution. Less demanding in computational time and memory, a 1/12º grid and bathymetry (GOM 0.08) is built from the 1/25º grid and bathymetry of the Navy Research Laboratory Gulf of Mexico configuration (GOM 0.04) to validate the model. This configuration has 20 sigma-0 layers and no atmospheric forcing. In order to avoid reflections due to the tides at the boundaries (southern, eastern and northern boundaries) and a pile up of energy in the domain, radiative boundary conditions are applied on the barotropic components of the velocity. Tides are modeled through a Local Tidal Potential (astronomical forcing) applied over the domain and through the open boundaries where barotropic tidal transports and elevations derived from the Egbert and Erofeeva (2002) model are prescribed. Four tidal constituents, that represent 90% of the tidal variance in the region (Kantha, 2005), are considered in our experiments: two diurnals (O_1 and K_1) and two semi-diurnals (M_2 and S_2). Amplitudes and phases of each tidal constituent, extracted from the barotropic tidal model *GOT99* (Ray, 1999), are presented Figure 1.

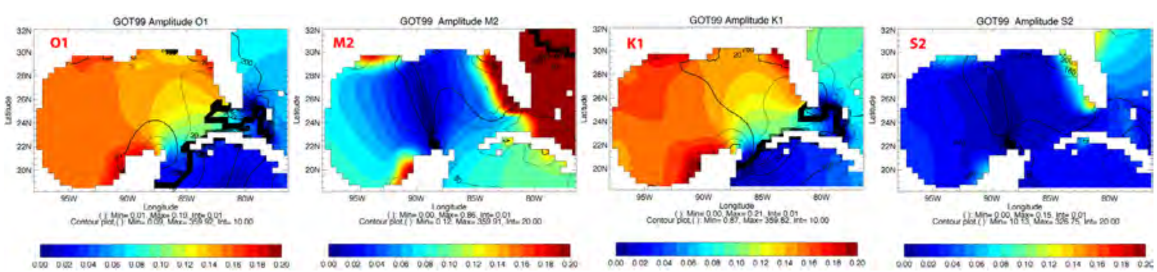

Figure 1: Amplitude (colors) and phase (contours) of O1, M2, K1 and S2 constituents in the GOT99.

The main goal of this study being the representation of baroclinic tides, we test the model in reproducing the amplitude and phases of the tides using a range of stratification going from a quasi-barotropic density profile to a baroclinic density profile corresponding to the mean stratification of the Gulf of Mexico in summer. In addition, the impact of two different radiative open-boundary conditions on the tidal solution is tested: the Flather (1996) boundary conditions, which is used by most of the tidal community and the Browning and Kreiss (1982) boundary conditions which is a radiation condition already implemented in HYCOM. While the *Flather* boundary conditions impose only the gradient of the incoming flow invariant to zero, the *Browning and Kreiss* boundary conditions impose the gradient of the incoming and outcoming flow to zero. The model is run for 30 days for each experiment and all the analysis are done after day 5, time after which the model has reached an equilibrium state (the tidally averaged energy in the domain neither increases or decreases). We use the t-tide software to extract tidal harmonics.

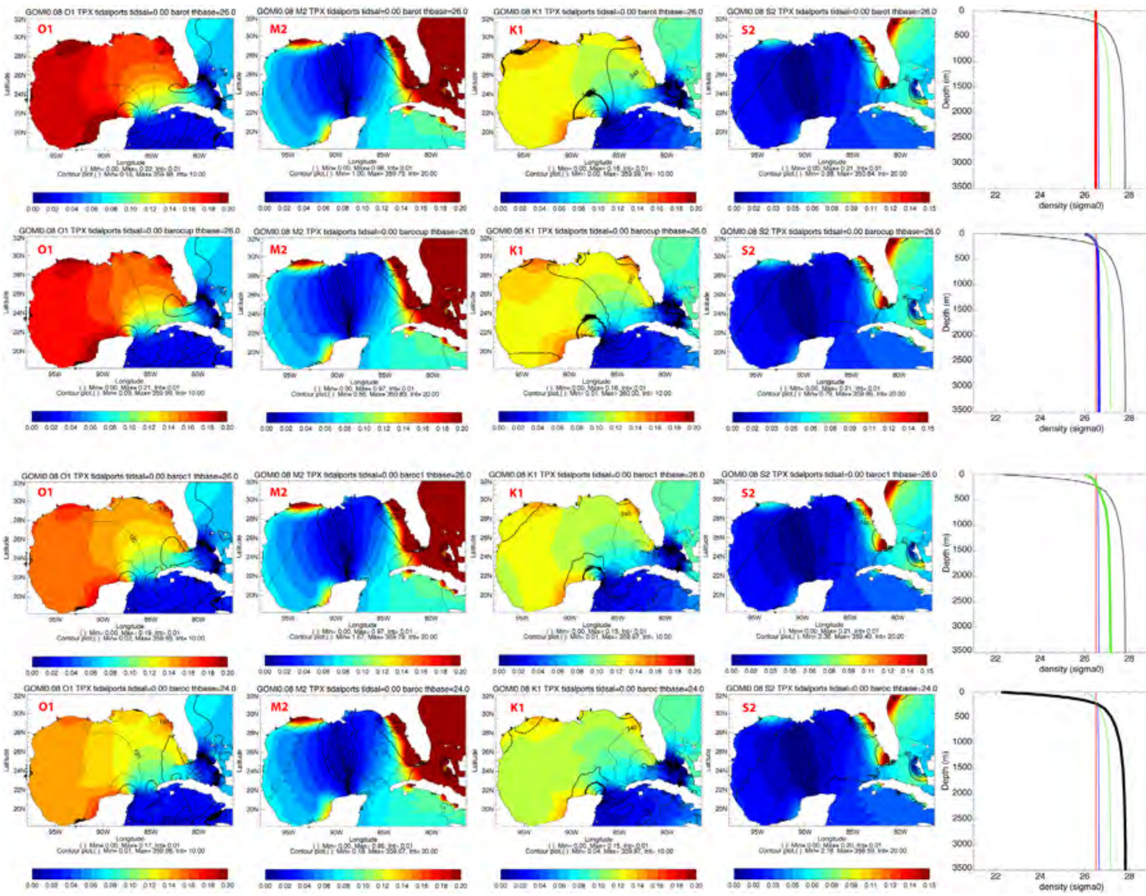

Figure 2: Amplitudes and phases of O1, M2, K1 and S2 in the 1/12º configuration for different density profile from quasi-barotropic (top) to baroclinic corresponding to a mean summer density profile in the Gulf of Mexico. These experiments use the Flather boundary conditions.

First, the *Flather* boundary conditions are tested (Figure 2). The semi-diurnal tides amplitudes and phases compares well with the *GOT99* and previous studies (Kantha, 2005; Gouillon et al., 2010) for each stratification. In particular, the location of the M_2 amphidromic point (zero tidal elevation at any time) is well located north of the Yucatan peninsula and an amplification of the semi-diurnal tides is present on the West Florida Shelf (~30 cm in M2 and ~15 cm in S2) as expected (Clarke and Battisti, 1981). The spatial homogeneity of the diurnal tidal amplitudes and co-tidal lines compares well to *GOT99* also for each stratification but the amplitudes are affected by the change in stratification. In a quasi-barotropic setting, the amplitude of O1 is over-estimated by 3-4 cm cm while K1 is under-estimated by 2-3 cm (Figure 2 top-panel). Increasing the stratification, O1 amplitude decreases from 18-19 cm to 14 cm and K1 amplitude decreases from 12 cm to 10 cm. While O1 is still well in the range of the observations in the baroclinic experiment, K1 amplitude is ~4-5 cm too weak for each stratification. Second, the *Browning and Kreiss* boundary conditions are tested using the same stratifications as the previous experiments (Figure 3). Similarly to the experiments with the *Flather* boundary conditions, the semi-diurnal tides are well represented for each stratification when the *Browning and Kreiss* boundary conditions are used. However, unlike the experiment with the *Flather* boundary conditions, the diurnal tidal amplitudes remain close to 14-15 cm for each stratification.

While we still see a decrease of the amplitude between the quasi-barotropic case and the baroclinic case, this decrease does not exceed 2 cm. The co-oscillation phenomenon seems therefore to be better represented when *Browning and Kreiss* boundary conditions are used.

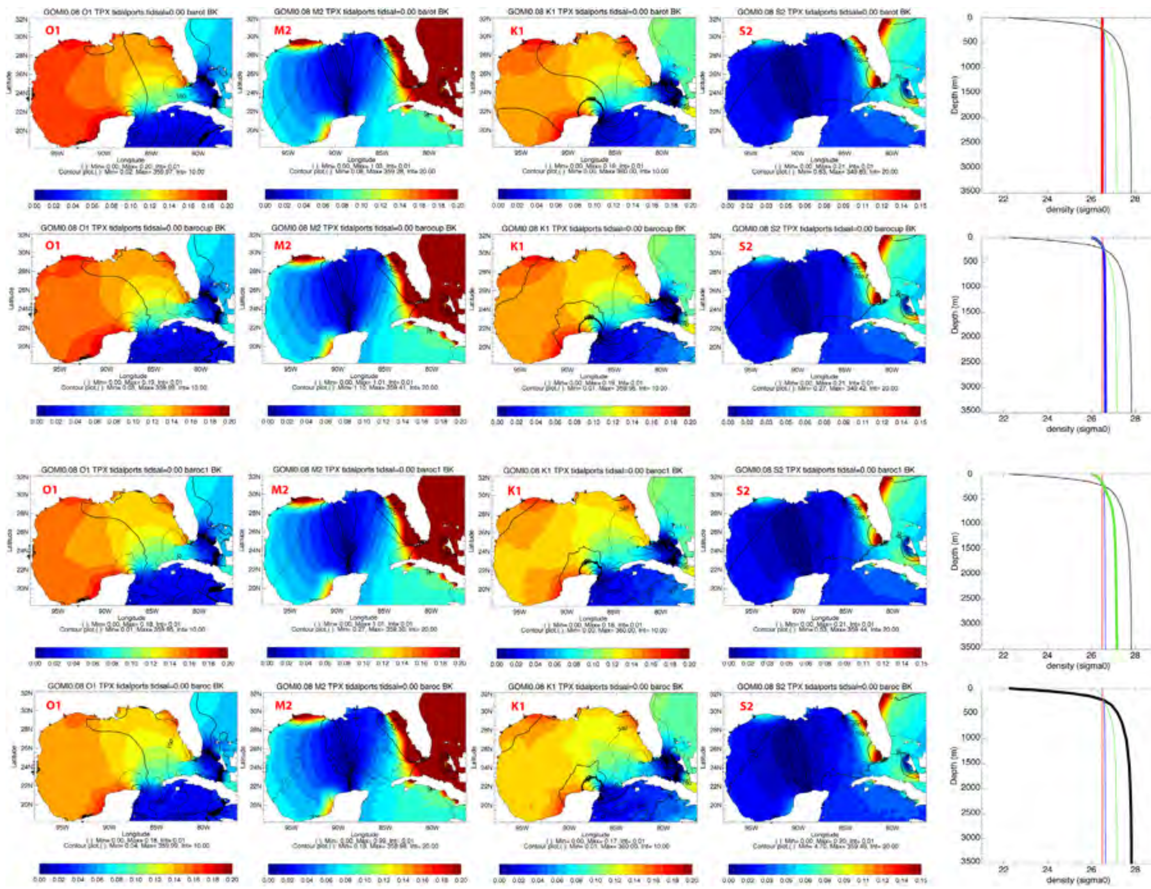

Figure 3: As Figure 2 but using Browning-Kreiss open-boundary conditions.

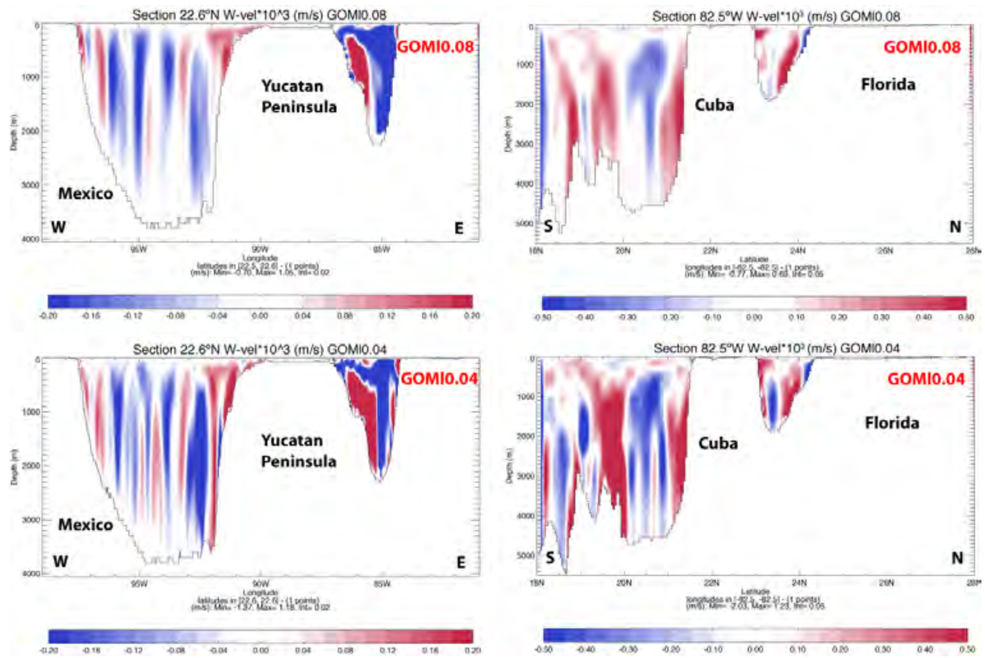

Figure 4: Snapshot of a cross-vertical section at 22.6ºN (left) and 82.5ºW (right) of vertical velocities of the baroclinic simulation (black density profile Figure 2) for the 1/12º on top and 1/24º on the bottom.

Internal tides characteristics were evaluated by comparing first, the vertical velocity (W-vel) on two sections (22.6ºN and 82.5ºW) in the 1/12º and the 1/25º configurations for the baroclinic experiment (Figure 4). In the 1/25º, fine internal wave structures are seen due to a better horizontal resolution that resolves higher internal wave modes as well as a higher magnitude to the vertical velocities compared with the 1/12º configuration velocities. This feature is even more noticeable in the section at 82.5ºN that covers the "entrance" of the Yucatan Strait and the Florida Strait (Figure 4, right) where the tidal flow from the Atlantic "interacts" with the tidal flow from the Gulf of Mexico. The next step of this study will be the assessment and investigation of Gulf of Mexico regions in which strong internal wave related mixing is produced, through the quantification of tidal conversion rates. Focus will be made on shelf regions where the internal wave mixing is the most important.

Data assimilation and tides

Two subtasks of the current data assimilation effort are 1) to develop and validate data assimilation strategies for tide resolving configurations and 2) to reduce model error by controlling the bias and drift common to all ocean models. Work elsewhere in the ocean modeling community have sought to address these two issues. First, Counillon et al., (personal communication) assimilate into a tide-resolving HYCOM by filtering the tidal signal from the model and assimilating the de-tided altimeter data to correct the mesocale processes. Second, Thompson et al. (2006, 2007) have proposed a simple and efficient method spectral nudging method for reducing drift and bias in eddy resolving ocean models. Here we address these issues in an integrated fashion by implementing a scale selective data assimilation technique (e.g., Xie et al 2010). Our approach has been to develop and implement an efficient recursive filter to separate signals of interest from instantaneous model output. Towards this

end, we have developed and implemented a recursive filter for HYCOM. This filter is being tested in twin experiments assimilating synthetic altimeter data into the 1/25º Gulf of Mexico HYCOM (GOM-HYCOM described in previous section). The experiments are designed to systematically evaluate the assimilation products and identify viable data assimilation strategies which will then be validated in tide resolving hindcasts. The data assimilation schemes available for HYCOM (e.g., Srinivasan et al., 2011) have been shown to accurately capture the mesoscale eddy field in non-tidal configurations. However, assimilating data to correct the mesoscale eddy field in the presence of tidal motions has some subtleties and practical challenges that need some consideration. Altimetric data is generally the most effective way to correct the mesoscale eddy field in eddying ocean models. The altimeter data currently assimilated into ocean models is pre-processed to remove the tidal signal, the geoid and the inverse barometer effect. This is made available as sea level anomalies (SLA). While it might be possibe to assimilate the raw altimeter data directly it is complicated and the benefits are not clear. Our initial attempt will therefore use the detided data to correct the mesoscale field. In general, to assimilate detided data into a model with both tidal and non-tidal motions requires the de-tiding of the model data before assimilation. This is true even in the case of SLA since the signal which will be used to generate the model counterpart of the observations has a contribution from tides. Therefore attempts to assimilate data into tide-resolving model such as Counillon et al. (personal communication) have utilized what has been termed as a Scale Selective Data Assimilation (Xie et al., 2010). In this method, a three step procedure is used: 1) low-pass filter model outputs to extract the mesoscale circulation, 2) data assimilation using the de-tided forward model, 3) combine tidal and the corrected non-tidal component and integrate further.

While this procedure is relatively straightforward, there are a few practical issues to consider when applying it to a 1/25º global model. A workable separation of the tidal and non-tidal motions can be most simply achieved by a 25 hour running mean filter but this does not give explicitly the tidal components. Further, the non-tidal component is a 25 hour running mean which might make it difficult to implement First Guess at Appropriate Time (FGAT) introduce a bias when instantaneous data are assimilated. Alternatively, saved outputs can be used to derive and remove the tidal components but this requires harmonic analysis and can be very time consuming and disk space intensive. One way to handle these issues is to design a filter that allows corrections within specified frequencies and wavenumber bands as done by Thompson et al. (2006, 2007) and Wright et al. (2006). Thompson et al. designed a recursive filter designed to nudge the model in frequency and wavenumber bands that cover only the frequencies and wavenumbers resolved by the climatology. A similar approach can be taken here to apply corrections only in frequencies and wavenumber bands that are representative of mesoscale signals. In contrast to Thompson et al. however, we use this approach to assimilate data instead of nudging the model.

We use a recursive filter to extract the tidal components and the mesoscale signal from the model state.

We use the standard NRL 1/25º GOM-HYCOM configuration for all experiments reported here. We first tested the online filter by running the model with the O1 tide and checking if the filter is able to extract the signal. For verification, hourly outputs were saved for ”classical” harmonic analysis with the widely used matlab t tide toolbox. Figure 5 illustrates the performance of the online filter. The online recursive filter is able to extract the O1 signal and compares favourably to the harmonic analysis.

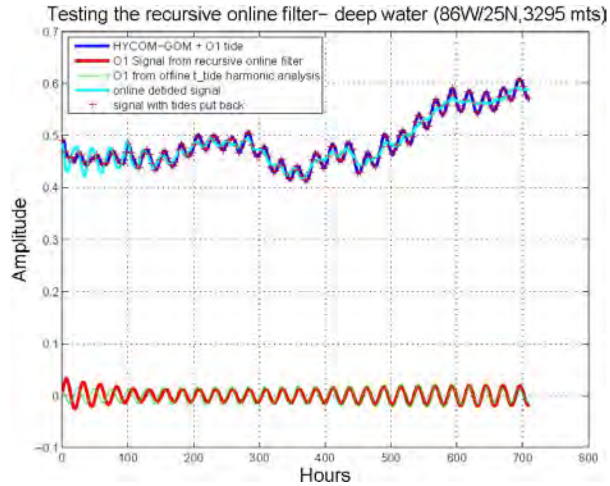

Figure 5: Performance of the recursive filter to extract the O1 tide component from a HYCOM simulation. The online filter is able recover the O1 tidal signal in about 8 days and thereafter is comparable to classical harmonic analysis

After verifying the ability of the filter to detide the model outputs experiments were setup to test the assimilation of surface elevation data in the presence of tides. Three different one month simulations were performed for the twin experiments. First a model simulation was run without tides for a month. This run was used to generate the synthetic altimeter data. Outputs from this run were also saved to to measure the performance of the assimilation schemes. A second simulation was performed with a tidal configuration assimilating synthetic data. This simulation was started from a different initial condition (simply a model state chosen at a different phase of the Loop Current extension) and had only the O1 tide switched on. Data from the truth was assimilated into this run. These model runs were forced by 3 hourly COAMPS derived wind stress, wind speed, heat flux and precipitation. Climatological boundary conditions are used for nesting purposes. The barotropic tidal transport and elevation are prescribed at the open boundaries and are derived from the Egbert and Erofeeva (2002). After removing the O1 tide from the model outputs data was assimilated into the model using a reduced order filter and tides were then put back. The initial results suggest that our implementation of the recursive filter for detiding and subsequent assimilation work well for altimeter data assimilation (Figure 6). The performance of the assimilative run is clearly better compared to a third model run (for reference) without assimilation but with tides and starting from the same state as the assimilatve run (Figure 6).

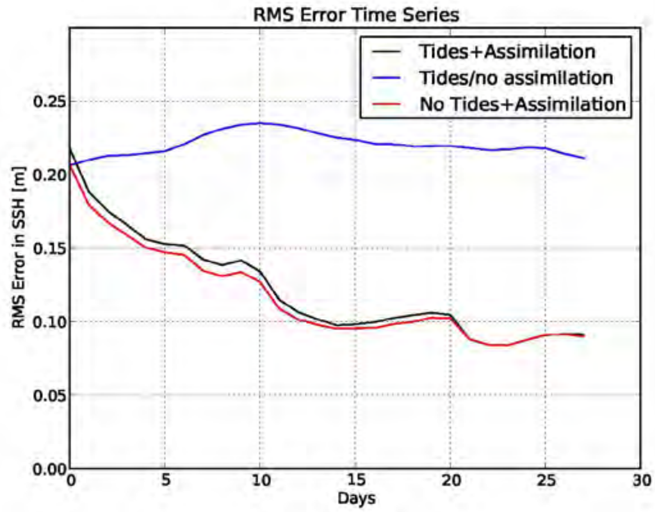

Figure 6: Results from initial twin experiments assimilating synthetic SSH. The filter allows efficient detiding of the model SSH fields and assimilation of the detided SSH data. The model performance is clearly improved in the assimilative case -assimilatve model performance in the presence of tides is almost as good as the not-tidal case.

Arctic Ocean

The major goal of the work is to develop, validated, and improve a fully coupled modeling system of the Arctic Ocean and sea ice. Within the AOMIP, FSU and BRL participate in coordinated AOMIP experiments and provide model results for community model intercomparisons and process study in the Arctic. The ocean model component is based on HYCOM (HYbrid Coordinate Ocean Model) which vertical discretization is a combination of isopycnic, terrain-following and geopotential vertical coordinates (Bleck, 2002; Chassignet et al., 2003). The sea ice component is based on CICE 4 sea ice model (Hunke and Lipscomb, 2004). The model uses Arctic dipole grid with two configurations: 0.72 degree (ARCc 0.72) and 0.08 degree (ARCc 0.08) horizontal resolutions. Analysis of the test run with ARCc0.72 performed at NRL SSC with simplified bottom topography (experiment "NRL-ST", Table 1) revealed noticeable biases in the simulated temperature and salinity as well as ocean circulation in the Arctic. For instance, temperature in the Atlantic Water layer (defined as water mass with T > 0˚C) in the simulation was found to be colder by ~1.5°C than the core temperature of the Atlantic Water derived from climatological fields. In the test experiment, warm Atlantic water did not penetrate in the Arctic Basin contradictory to the climatology fields. Observations and other model studies suggest that the Atlantic water flows along the shelf edge in Eurasian Basin in cyclonic sense and spreads over the Canada Basin forming warm layer with temperatures above 0°C in the depth range from ~ -800 to -150 m. A strong negative anomaly in the temperature field at 200 – 700 m off the Kara Sea shelf was simulated in the model. These results demonstrated that Atlantic water circulation was misrepresented in the ARCc0.72 model. A possible source of error could be inaccurate approximation of the Arctic Basin bottom topography in ARCc0.72 experiment NRL-ST ("T06" in Table 1, Fig. 1, left): Eurasian shelves are closed (the coastline is at 50 m depth); major channels in the Canadian Arctic Archipelago are not resolved; Bering Strait is closed. These artificial alterations in the basin's topography might have affected the mesoscale circulation in the Arctic Ocean leading to different distribution of water masses compared to climatological fields. To verify this assumption, a realistic bottom topography was

prepared ("T02" in Table 1) and employed in the ARCc0.72. Forcing fields similar to experiment NRL-ST were used for this experiment ("RT"). The model was started from rest with T/S fields from PHC 3 climatology (http://psc.apl.washington.edu/POLES). The model was run 1 year with climatological forcing and 5 years with repetitive 0.5 degree 3-hourly NOGAPS atmospheric fields (*Goerss and Phoebus*, 1991; *Bayler and Lewit*, 1992) for 2003. At the lateral OBs, the model was relaxed to the climatological fields. After the spin up, the model was run for 2003 -2009. The main result of experiment 040 was more realistic circulation of Atlantic Water in the Arctic Ocean basin compared to the results from "ST-NRL" experiment. In "RT" experiment, the warm layer formed in the Eurasian Basin and Canada Basin within the depth range from -900 to -200 m, in general agreement with climatological data. To further analyze model sensitivity to different topographies, several model experiments are performed (Table 1). The experiments are twin simulations with "RT" experiment and use same topography (T02) but with artificially imposed changes: such as closed Bering Strait (T03), closed channels of the Canadian Arctic Archipelago (T04), and closed Kara Sea strait and 100 m depth sill to limit the interaction between the Barents and Kara Seas (T05).

Table 1. Model Experiments with different topographies

Topography	ARCc0.72 Experiment	Description
T06	ST-NRL, ST	• Min depth is –50m; • Eurasian shelves are closed; • Bering Strait is closed; • CAA is represented with 1 wide channel.
T02	RT	• Min depth is –10m; • Eurasian shelves are open; • Bering Strait is open; • CAA is represented with 1 wide channel.
T03	RT-B	Same as T02 but closed Bering Strait
T04	RT-C	Same as T02 but closed CAA
T05	RT-K	Same as T02 but closed Kara Sea strait and artificial 100 m sill in the Barents Sea (to restrict Barents Sea – Kara Sea interaction)

One outcome of the above sensitivity experiments show that the target densities and distribution of the vertical layers is such that Atlantic Layer is not well resolved. Besides, the deep ocean is represented by a single layer. A new set of target densities is suggested which resolve better both the Atlantic Water layer and the deep ocean. Model experiments with the new vertical discretization is run in a similar fashion as other FSU ARCc0.72 experiments. Preliminary analysis of the model run with new target densities (Figure 7) indicates marked improvement in simulation of the Atlantic Water circulation and thermohaline structure in the Arctic Ocean. The 0.08° resolution HYCOM/CICE model is under evaluation in collaboration with NRL.

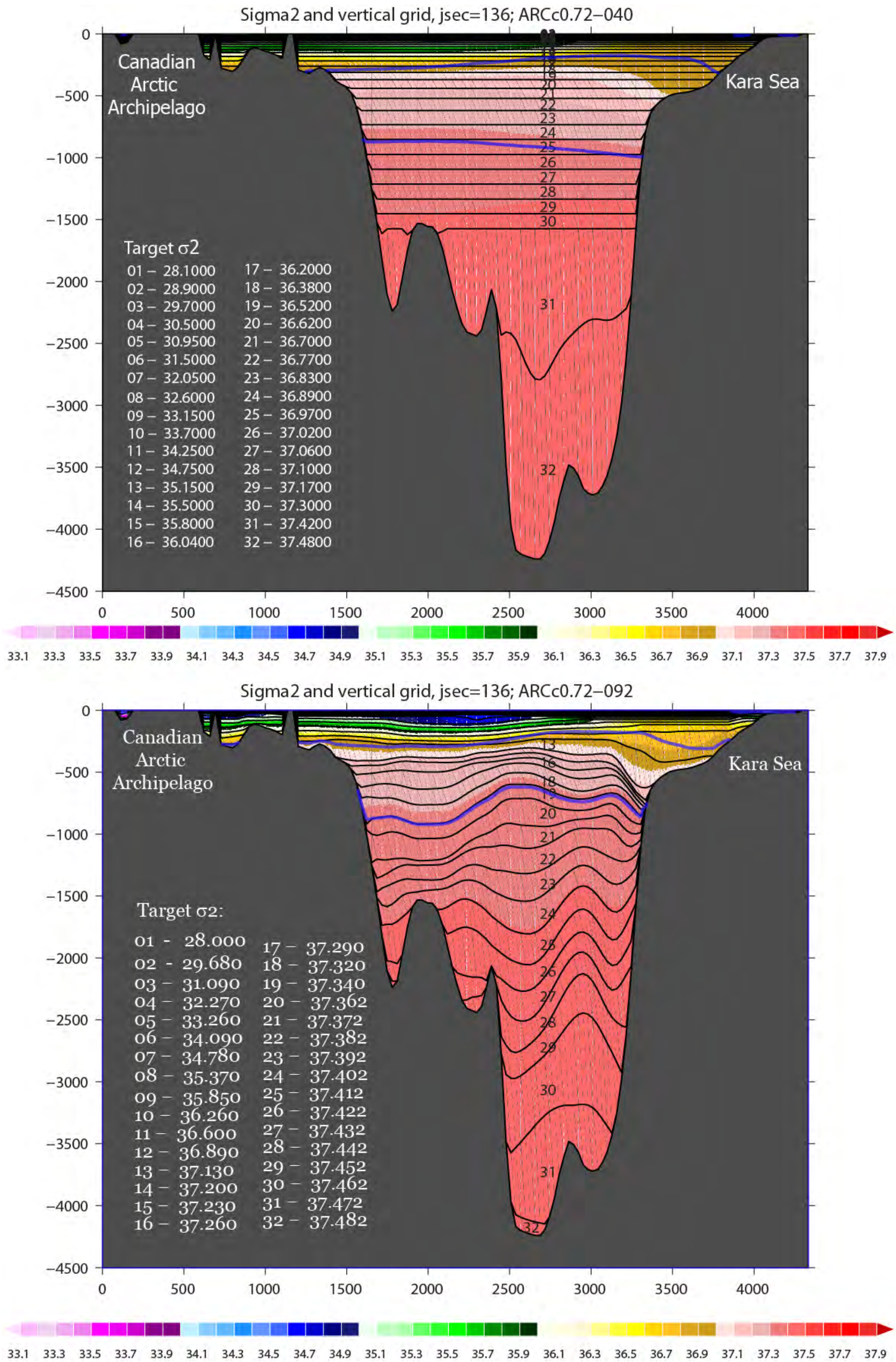

Figure 7. Density fields (σ_2) in the Arctic Ocean cross-section from ARCc0.72 simulations with different target densities. Blue line highlights the Atlantic Water Layer. Black curves delineate isopycnal interfaces. Top: Model with "original" target densities. Bottom: Model with new target densities.

IMPACT/APPLICATIONS

The 1/25° (3.5 km mid-latitude) resolution is the highest so far for a global ocean model with high vertical resolution. A global ocean prediction system, based on 1/25° global HYCOM with tides, is planned for real-time operation starting in 2012. At this resolution, a global ocean prediction system can directly provide boundary conditions to nested relocatable models with ~1 km resolution anywhere in the world, a goal for operational ocean prediction at NAVOCEANO. Internal tides and other internal waves can have a large impact on acoustic propagation and transmission loss (Chin-Bing et al., 2003, Warn-Varnas et al., 2003, 2007), which in turn significantly impacts Navy anti-submarine warfare and surveillance capabilities. At present, regional and coastal models often include tidal forcing but internal tides are not included in their open boundary conditions. By including tidal forcing and assimilation in a fully 3-D global ocean model we will provide an internal tide capability everywhere, and allow nested models to include internal tides at their open boundaries.

TRANSITIONS

None.

RELATED PROJECTS

The computational effort is supported by DoD HPC Challenge and non-challenge grants of computer time. In FY11, 1/25° and 1/12° global HYCOM ran under the FY09-11 DoD HPC HYCOM Challenge grant.

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